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Review of energy efficient direct pump controlled cylinder electro-hydraulic technology

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ABSTRACT

Hydraulic cylinder is an indispensable linear actuator in high power applications like construction machinery. In order to reduce the energy consumption, the noise and the waste oil disposal pollution of the hydraulic cylinder control system, the most direct method is adopting the direct pump control technology which eliminates the throttle losses in the main power line. In such system, by changing the speed or the displacement of the pump, the pressure and volume flow will be matched with the need of loads. To date, research works in this field have been reported in many articles, but they are scattered and written in different languages. An overview which can summarize the latest development of this technology appears to be necessary. This paper provides a comprehensive review on this technology, aiming at clarifying recent advances and outlining potential challenges in the research and application of this technology. The review mainly covers three parts: system structure, control, and derived energy recovery system. Also the evolvement of the electro-hydraulic cylinder control system is introduced. The review indicates that attentions should be paid to the control and energy recovery plan of the direct pump controlled cylinder system, and to the newly proposed asymmetric pump controlled differential cylinder technology. It is envisaged that the information gathered in this paper will be a valuable one-stop source of information for researchers, as well as providing a direction for future research in this area.

Contents

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1. Introduction

Electro-hydraulic system as one of the fundamental components has been applied in many equipments, such as the construction machines, the agricultural machines, and the aeroplanes. Common to these applications is that high power is often required to perform the desired work, for example moving material or lifting heavy weights. The power for such drives is often generated by a centralized source, usually an internal combustion engine or a high power electric machine. Using fluid power systems the power is easily distributed via hydraulic lines to either linear or rotary drives. It is estimated that by the year of 2000, the world market of electro-hydraulics is about 30–35 billion dollars per year, and is in steady growth. Meanwhile, energy saving concerns for hydraulic system has been raised with the numerical application of heavy equipments. Electro-hydraulic system mounted equipments often work around the clock and output high power in handling heavy loads. The energy consumption and the waste gas emission of such systems therefore stay high. Take one of the most popular construction machines, 20-t load sensing controlled hydraulic excavator as an example. Such type excavator usually requires a diesel engine of more than 110 kW, which consumes at least 33litre fuel in an hour. The amount of NO_X and CO emitted by this machine is considerable. But only 30% of the consumed energy is used in moving loads. While more than 60% of the energy is consumed in power losses and driving of hydraulic systems [1]. Therefore even a small improvement in the hydraulic system efficiency will have a significant impact on the total energy efficiency of the machine.

Previously, several literature reviews have been presented regarding the application of electro-hydraulic technology in various fields for energy saving purpose. Zhang et al. overviewed the application of hydraulic cylinder based wave energy generation in China [2]. [3,4] reviewed the high pressure hydrostatic technology in energy efficient food production and processing. And the status of hybrid construction machinery, one of the most important application fields of the electro-hydraulic technology, was overviewed in Ref. [5]. Above papers have presented the importance of electro-hydraulic technology in energy saving or generation applications, but the latest development of electro-hydraulic circuit and control technology has not been reviewed. Based on the type of the actuator, such technology can be classified as two types: rotary motion control, i.e. hydraulic pump/motor, and linear motion control, i.e. hydraulic cylinder. Hydraulic rotary motion control is usually implemented in applications like the slewing system and the walking system of construction machines and some low power applications. The control of the hydraulic pump/motor is simple due to the symmetric distribution of the pressure in the system. The hydraulic cylinder has attracted more attention and has gained widely applications. Compared with electromechanical linear actuator and pneumatic cylinder, the high output force of the hydraulic cylinder system makes it indispensable in high power linear motion applications like press machine, bending machine, construction machine, short distance lifting equipment, etc., making the hydraulic cylinder the most emblematic actuator in electro-hydraulic systems. But hydraulic cylinder control system also faces limitations. The energy efficiency of hydraulic control system is lower than that of the electromechanical system and pneumatic system. And the controllability is also poor due to the significant nonlinearity and asymmetric of the system, especially in the differential cylinder control system. The poor energy efficiency and control performance of the cylinder control system significantly undermined the performance of the overall equipments. So over the past decades, efforts have been focused on improving the energy efficiency and control performance of the hydraulic cylinder control system in terms of modifying the system structure and implementing advanced control approaches.

In this paper, state of the art of the pump controlled cylinder technology will be reviewed. First the evolvement of cylinder control system is presented to introduce the advantage of the pump control technology. Then the direct pump controlled double rods cylinder technology and direct pump controlled differential cylinder technology are overviewed respectively in Sections 3 and 4. Existing control strategies for pump controlled cylinder system will be reviewed in Section 5. And the energy recovery technology based on the pump controlled cylinder is also discussed in Section 6. In the end the major challenges that this technology faces will be summarized. The aim of this review is to provide a comprehensive perspective on the challenges and tendency of this technology for the researchers and help them seeking breakthroughs for hydraulic system.

2. Evolvement of hydraulic cylinder control system

Based on the circuit types, hydraulic cylinder control system can be classified as valve controlled system and pump controlled system. Valve controlled hydraulic systems have been widely applied in conventional equipments and machines implement due to its low cost and simple structure. However it faces an obvious drawback, the enormous energy loss, i.e. throttling loss at the control valves [6,7]. Study on the energy analysis of fluid power system has shown that 35% of the input energy of a valve controlled system is consumed in controlling valves. Such poor energy efficiency will lead to the high engine installed power and will generate great amounts of heat during the operation of the equipment. And overheat is also a significant reason that causes breakdown of the machines. To decrease the temperature of the system, additional cooling system is required but it will also further increase the cost and the installed power of the equipments. And as an open circuit, valve controlled system usually needs large amount of hydraulic oil for the operation of the circuit, which to some extent increases the cost of the system and raises pollution problem when disposing the oil. Although the development of load sensing technique effectively reduces the throttling loss of the control valve, eliminating of such loss in valve controlled system is impossible.

Another type of hydraulic system is pump controlled system. Such system falls into two types, open circuit as shown in Fig. 1 (a) and (b) and closed circuit which is also called direct pump controlled system, as shown in Fig. 1(c) and (d). In open circuit pump controlled systems, control valves still place important roles in controlling the flow direction of the oil in the chambers of the cylinder, so the energy efficiency of the system is directly affected by the efficiency of the valves. Some schemes still need throttling valves in the main power lines. And due to the throttling losses in the control valves and pressure losses, the energy efficiency of the open circuit system is degraded.

In order to eliminate the throttling loss and reduce the overall energy consumption of hydraulic system, direct pump controlled system was proposed. As can be seen from Fig. 1(c) and (d), pump controlled cylinder system, different from valve controlled system, is a closed-control structure, in which both chambers of the cylinder are connected with the pump. The primary power sources of these systems are usually electric machines. Compared with the valve controlled system and open circuit pump controlled system, the closed pump controlled system, which does not need control valves, suffers no throttling loss in the main power lines and needs less hydraulic fluid, i.e. oil, in the operation. And based on the pump controlled system, energy recovery solutions for kinetic energy and potential energy are possible. Hence the installed

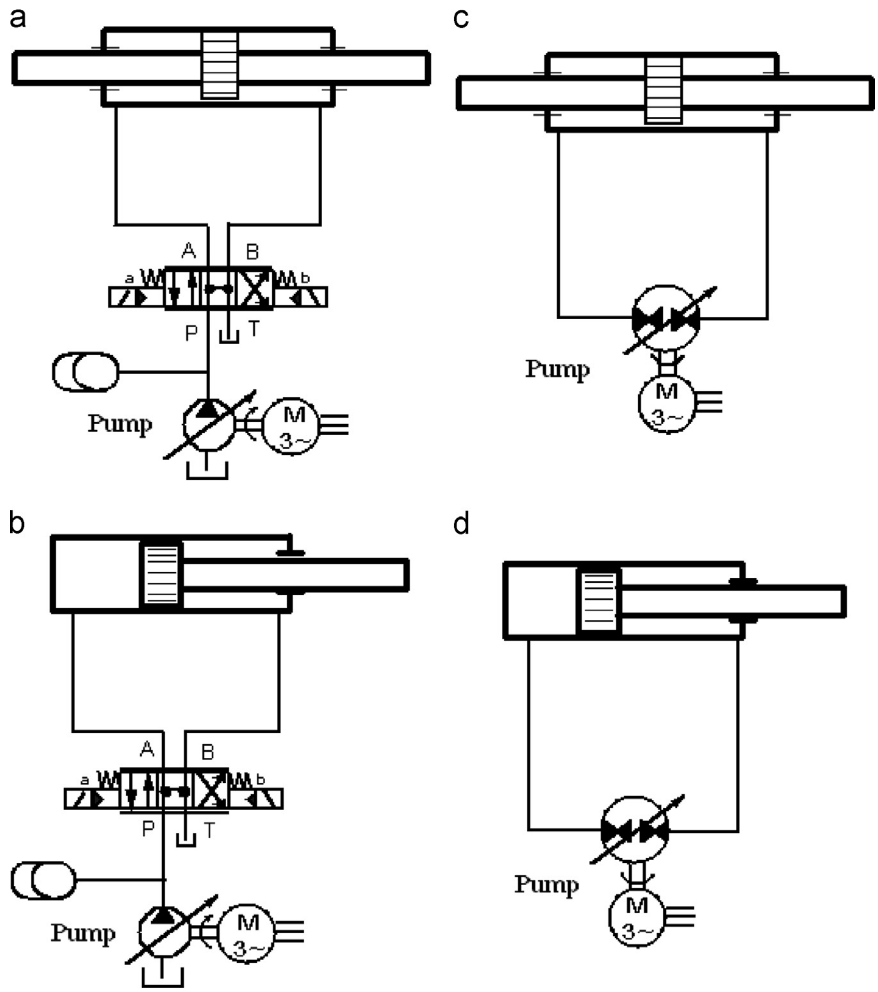

Fig. 1. Basic schemes of open circuits (a and b) and closed circuits (c and d).

engine power, overall equipment energy consumption, the generated heat will be greatly reduced. Investigation on the energy efficiency comparison of the two kinds of hydraulic systems showed that the energy efficiency can be improved more than 40% by using advanced pump controlled systems. One more advantage of utilizing pump controlled system is that the power can be delivered by wire instead of by steel pipes. Hence the pump controlled system is obviously a better solution to realize the green in fluid power system, i.e. low noise, high efficiency, less pollution, making it the developing trend of electro-hydraulic control technology.

Although the energy efficiency can be improved enormously with direct pump controlled technology, limited by the dynamic performance of the pump, such principle could just be used in the pump controlled motor system with large power in the early time. It is not until 1980s that control of the cylinder closed loop with pump became possible. By using pump displacement and valve stroke double closed loop controller, the dynamic response performance of axle and radial piston pump reach almost the same level as normal proportional valves. With higher supply pressure their frequency response in small signal range reaches more than 50 Hz [8,9], which is sufficient for today's most industrial and mobile applications. Based on the type of the cylinder, the technology falls into two kinds, the pump controlled double rods cylinder, as shown in Fig. 1(c) and the Pump Controlled Differential Cylinder, as shown in Fig. 1(d). The development of the system circuit of both the two systems will be presented in the following sections.

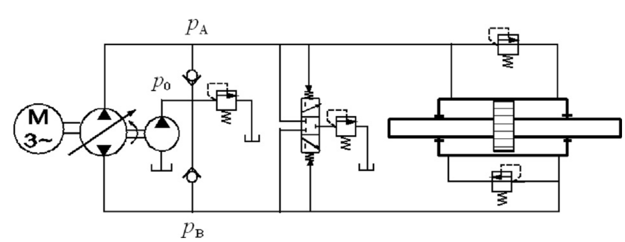

Fig. 2. Pump control cylinder circuit with one chamber preloaded.

3. Pump controlled double rods cylinder

In 1973 and 1979, Hahmann and Spockhoff introduced the circuit principle of pump controlled motor into the control of hydraulic cylinder in their dissertations, and researched the static and dynamic performance of the pump controlled cylinder system [10,11]. The circuit is shown in Fig. 2.

This hydraulic system uses an oil exchanging valve with constant back pressure to exchange heat; only one chamber of the hydraulic cylinder is preloaded. Therefore the natural frequency of the system is low, which negatively affects the dynamic performance of the system.

In 1988, Berbuer proposed a new cylinder preload principle which consists of a constant pressure source and orifices, as shown in Fig. 3.

With this new principle, both chambers of the cylinder are preloaded with hydraulic pressure, the natural frequency and load rigidity of the pump controlled cylinder system are increased,

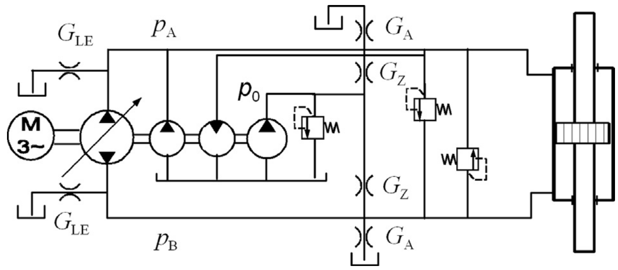

Fig. 3. Pump controlled double rods cylinder circuit with two chambers preloaded.

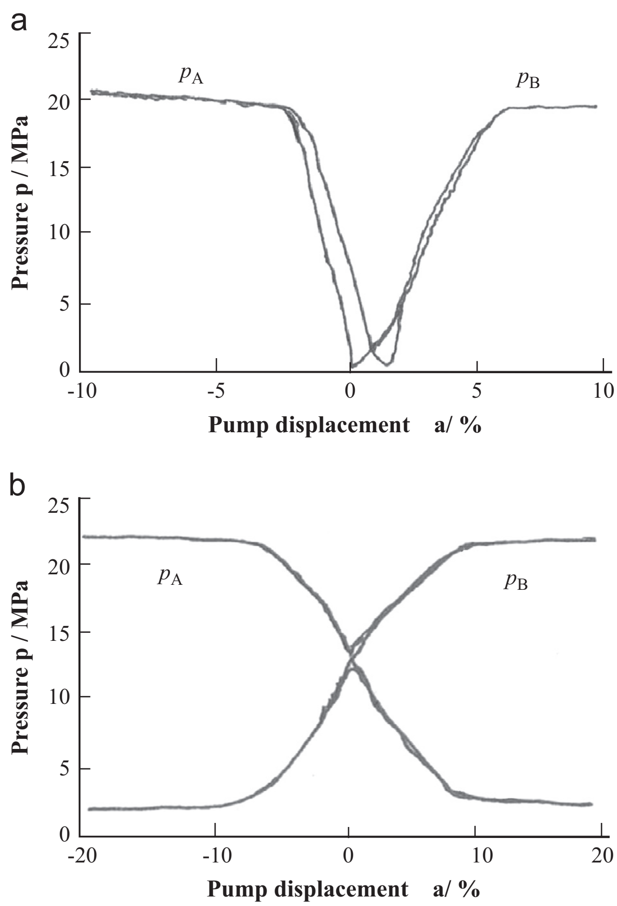

Fig. 4. Pressure gain curves of pump controlled double rods cylinder.

making the system possess a similar characteristic as the valve control system [12]. But in this circuit one pump and one motor are required to exchange heat. Fig. 4 shows the pressure gain curves of the above two systems.

It is clear that only one chamber's pressure changes with the swing angle of the pump when adopting the traditional constant pressure control. But by adopting the two-chamber preload principle, the pressures in both chambers vary with the swing angle of the pump in the opposite direction at the same time. The pressures of both chambers are equal when no load is acted. And this balance pressure can be controlled by adjusting the value of the orifices. When the cylinder is accelerating or there is load force acted, pressures of both chambers change at the same time.

In 1990, German Company Parker Hannifin applied for the patent of a new pump controlled double rods cylinder system for the manipulator system of airplanes [13]. Servo motor is adopted to drive a constant pump. The system scheme is shown in Fig. 5.

The characteristic of this system is that two chambers of the cylinder are preloaded through two check valves by a constant low-pressure oil tank or a low pressure accumulator, and the leakage oil of the hydraulic pump is also led to the oil tank. The speed and the moving direction of the cylinder are controlled by the servo motor driven constant pump. In 1990, German Company Demag applied for a patent that applies this principle into the control of plastic injection modeling machine [14]. In 1992, German Company Liebherr proposed a close-loop controller for double rods cylinder based on the electronic controlled proportional pump and applied this technology in the airplane control system [15]. The circuit is the same as that shown in Fig. 5. But the constant displacement pump is replaced by a proportional pump, and a small pump is added to exchange the heat when cylinder is positioned. Kazmeier researched the double rods cylinder system for the airplane application. In his research, both constant pump controlled system and proportional pump controlled system were analyzed. And a fuzzy logic based control method was proposed to improve the static and dynamic performance of the system. The system was implemented on an A340 airbus and conventional steel pipes were replaced by the novel Power-by-Wire actuator system, which reduced the weight of the plane at about 700 kg. Safety and reliability of the plane was also improved [16]. Habibi and Goldenberg proposed the principle of direct pump controlled symmetric linear actuators [17]. Though the actuator was not a typical double rods cylinder, this system is applicable for double rods cylinders. The pump controlled double rods cylinder has also been applied in the flight control [18–21]. Kang et al. proposed a hydraulic power regulator for flight control system on the basis of a modified the direct pump controlled double rods cylinder system [22]. A hydraulic lock was introduced to improve the stiffness and energy efficiency of the system. But on the other hand the existence of proportional valve in the power line degrades the energy efficiency to some extent.

Double rods cylinder as a symmetric actuator is simple to control. But its application is limited by the small output force and the install space. At present the double rods cylinder control circuit design is no longer a research focus.

4. Pump controlled differential cylinder

Because of the requirements on the installation space and output force, at least 80% of the electro-hydraulic control system adopts the differential cylinder as actuator. Different from double

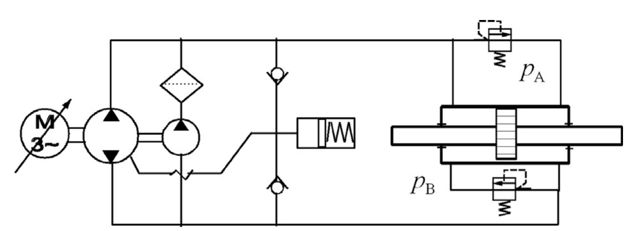

Fig. 5. Speed variable pump controlled double rods cylinder circuit.

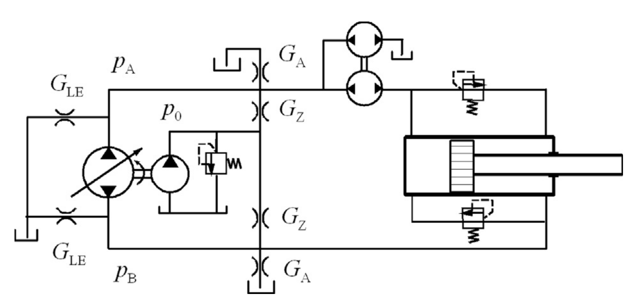

Fig. 6. Pump controlled differential cylinder circuit compensated with hydraulic transformer.

rods cylinder, the sectional areas of the two chambers are not equal. Therefore the oil flows of the two chambers are different, resulting in an asymmetric volume flow in the two ports of the cylinder. And unlike valve controllled system or open circuit, the asymmetric flow circulates in a closed loop in the direct pump controlled differential cylinder system. If cannot be compensated, this asymmetric flow will cause several problems like the inaccuracy of piston positioning and the poor control performance. The energy efficiency is also undermined if the asymmetric flow is not well compensated. Hence researches have been focused on the compensation method of the asymmetric flow in the differential cylinder system, as well as its applications and energy efficiency improvements. In this section, two types of systems will be introduced, system controlled by conventional pumps and system controlled by asymmetric pumps.

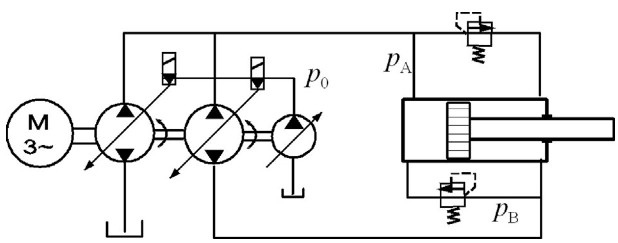

Fig. 7. Differential cylinder circuit controlled by two proportional pumps.

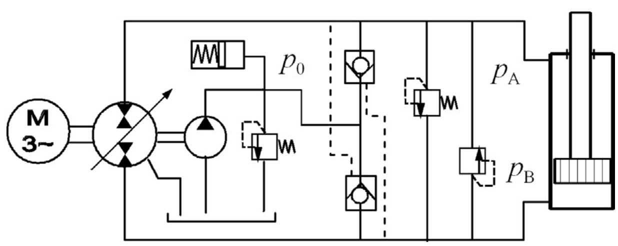

Fig. 8. Pump controlled differential cylinder with check valve balancing the flow [26].

4.1. Conventional pump controlled differential cylinder system

In 1994, Lodewyks. R, in IFAS RWTH Germany, put forward the circuit principles that use a hydraulic transformer or two coaxial-driven proportional pumps to compensate the asymmetrical flow in differential cylinder. Figs. 6 and 7 are the circuits [23]. Feuser from Rexroth, adopting the constant chamber pressure preload principle, researched the static and dynamic performance of the circuit in Fig. 7. This technology has been successfully used in the control of presser [24].

In 1998, Ivantysynova applied the direct pump control technology in construction machines. And their research revealed that compared with the valve controlled system, adopting the pump control technology can not only simplify the circuit, reduce the weight, improve the capability and energy efficiency, but also can make the control process easier. The research work showed a good future for the pump control technology [25]. Then Kahmfeld put forward the pump controlled differential cylinder circuit principle that adopts one hydraulic pump cooperated with two hydraulic controlled check valves to compensate asymmetrical flow. The system scheme is shown in Fig. 8 [26]. Meanwhile, the possibilities of applying this technology in concrete pump truck, wheel loader and multi-joint manipulator were researched [27,28].

In other studies, Japanese companies Yuken and Nachi developed the circuit principle shown in Fig. 8 into an integrated unit and put them into practice use. The product has been used in 6-DOF motion simulator, presser, and other fields. A similar system was proposed by the American company Vickers. They applied for the patent of the closed loop control of the differential cylinder

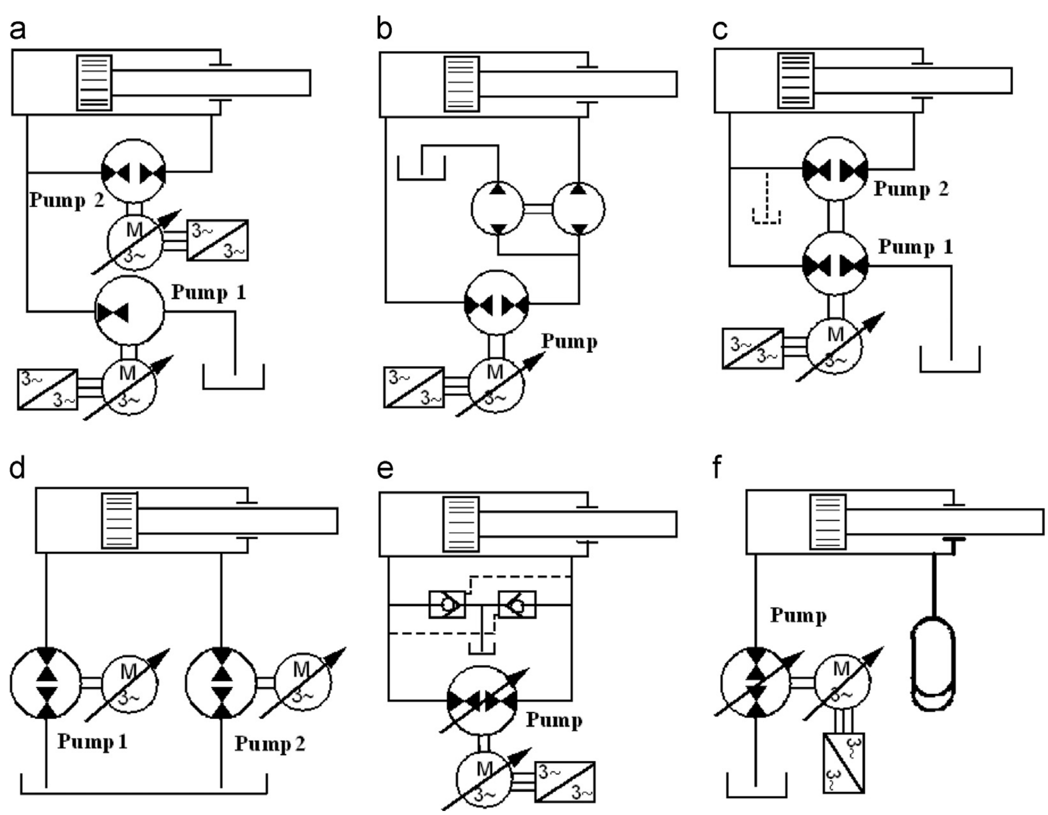

Fig. 9. Different asymmetric flow compensation circuits. (a) Closed circuit using two separate motor drive pump units (b) hydraulic transformer (c) closed circuit using connected two pumps (d) open circuit using two separate motor drive pump units (e) compensating by check valves and (f) retrieving oil by accumulator.

which uses a AC servo motor to drive the constant displacement pump and uses the hydraulic controlled check valves to balance the flow. This technology was later used in the plastic injection modeling machine [29]. Jiang et al. researched the system of ship steering controlled by the speed-variable pump [30]. Wang et al. proposed a system that balances the unequal flow through one of the pilot-operated check valves to the low pressure side whose pressure is close to the charge pump [31]. In another research, the asymmetric volume flow is compensated with a double-pump system [32].

Recent researches have demonstrated that the closed pump-controlled systems directly driven by servo motor, i.e. PMSM [45] or SRM [33], features many merits, such as wide speed range, high accuracy, high energy efficiency, high power density, etc. [34]. Helduser first proposed the concept of hydraulic pump-controlled system, driven by gear pumps and variable speed AC servo motors for injection molding machines [35]. Quan and Neubert researched the servo motor and constant pump closed loop controlled differential cylinder system. During the research, several circuit principles were suggested to compensate the asymmetrical flow of the differential cylinder. Especially the circuit that control the differential cylinder closed loop with two separate speed variable pumps, not only compensates the asymmetrical areas of the differential cylinder, making the dynamic performance in the two directions of the system the same, but also increases the driving power of the system. The newly developed sum-pressure principle preloads both chambers of the cylinder as two hydraulic springs that makes the system have same characteristic as valve controlled circuit. Experiments proved that the system has large output power and a similar static and dynamic performance as that of the proportional valve controlled system, but has higher energy utilization efficiency than the valve controlled system, making the circuit more suitable for the equipments that need large power [36]. Johansson and Petter studied the application of the pump controlled differential cylinder technology in the battle plane [37]. Cetinkunt et al. applied the pump controlled cylinder system in the bucket control of loaders, but asymmetric flow compensation was not considered [38]. Fig. 9 summarizes the existing compensation circuits for pump controlled differential cylinder system. Based on these circuits, some improvements or assisting circuits can be developed. Ho and Ahn proposed an assisted hydraulic circuit with three directional controlled valves for conventional hydraulic transformer [39].

In a comparative study, Zhang et al. investigated the energy efficiencies of different direct pump controlled cylinder systems in the injection molding machine application [40]. The energy efficiency of five different systems were studied and compared. They are induction motor driven constant pump, variable speed induction motor driven constant pump, induction motor driven variable displacement pump, variable speed induction motor driven variable displacement pump, and AC servo motor driven constant pump. Experiments were carried out on an injection molding machine. The research results confirmed that: in the partial load and no-load conditions, induction motor driven constant pump system suffers from the large overflow, throttle losses, and low efficiency. In the induction motor driven variable displacement pump system, the overflow losses are completely eliminated, however the big motor idling loss still exits. On this basis variable speed control is introduced to match the motor output power and the hydraulic load. And the energy efficiency is improved by 26.5%. The research also showed that the energy efficiency of the AC servo motor driven constant pump system is the highest, which can save 88% of the energy compared with induction motor driven constant pump. Also the structure and good dynamic performance can be optimized by applying the AC servo motor driven constant pump circuit.

4.2. Asymmetric pump controlled differential cylinder system

Though pump controlled differential cylinder system has been proved energy efficient in many fields, existed methods still face limitations. The asymmetrical volume flow cannot be easily compensated by single pump. High displacement check valves are needed as shown in Fig. 9(e), but the asymmetrical flow will increase energy exchange in the check valve, hence increasing the energy consumption of the system. To further reduce the energy consumption, auxiliary components are necessary. But unfortunately the auxiliary components will increase the cost and complexity of the overall system. In order to compensate the asymmetric flow, solutions shown in Fig. 9 have to sacrifice some of the advantages of the direct pump controlled circuit. To overcome this drawback, novel pump structure and system integration scheme are demanding.

Quan and his group studied the structure of the vane pump and piston pump. In their research, three novel pumps were designed and constructed [41,42]. The structures of these pumps are shown in Fig. 10. According to the fact that there are 4 ports in the double acting vane pump, the asymmetrical flow compensation system principle in Fig. 10(a) was proposed. By connecting the original pressure port to the piston chamber, the original suction port will be divided into two independent ports. One is connected with the ring chamber of cylinder and the other with the oil tank, basically compensating the area ratio of the differential cylinder with port, then through regulating the stroke of vane, the flow can be balanced. Based on this principle, piston pump can be modified, as shown in Figs. 10(b) and (c). One of the two original suction ports is divided into two ports. Port P_A is connected with piston chamber; P_B is connected with ring chamber. By regulating the length rate between port 1 and 2, or the piston numbers pass through the distributing flow port 1 and 2, the flow will be balanced basically. Due to the asymmetric structure of the new pumps, they are named as asymmetric pump, or three-port pump. Fig. 11 shows the plate of the new differential pump.

With this new pump, the cylinder control system no longer needs auxiliary valve to compensate the asymmetric flow of the differential cylinder. Moreover, the kinetic energy and the potential energy generated in the motion of the cylinder can also be directly recovered [43,44]. Furthermore, a PMSM driven asymmetric pump controlled cylinder system was investigated in [45]. The proposed system is shown in Fig. 12. The system can operate in four quadrants, as shown in Fig. 13. According to the direction of the force on the piston and the direction of the piston speed, charging and discharging of the accumulator is controlled. Therefore the energy can be directly recovered with only one pump.

To demonstrate the energy efficiency of the asymmetric pump controlled system, efficiency comparison was carried out. What Fig. 14 shows are the comparison results of the energy consumption in one working cycle that the pump controlled double rods cylinder, the double pump controlled differential cylinder and the asymmetric pump controlled differential cylinder separately controlling the same plastic injection modeling machine lamping unit. It is clear that the single asymmetric pump controlled system consumes less energy than the double-pump solution and reaches

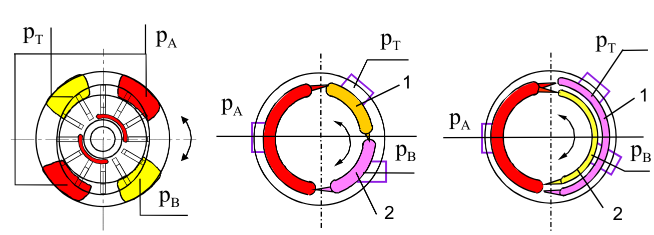

Fig. 10. Basic principle of asymmetric pump.

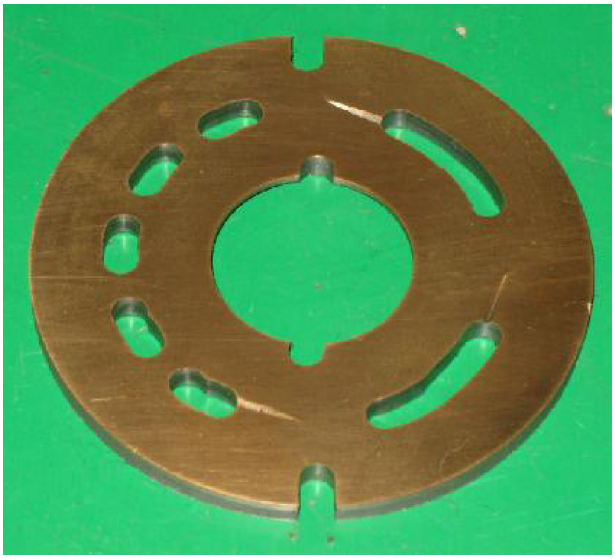

Fig. 11. Plate of the asymmetric pump [43].

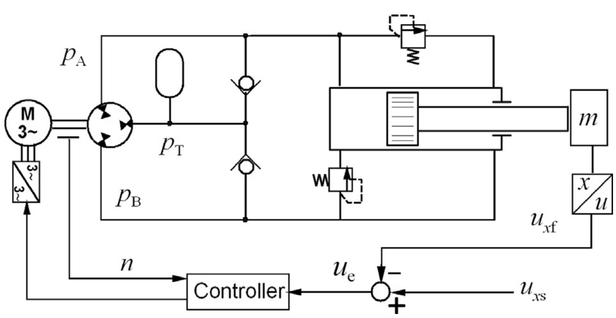

Fig. 12. Circuit of the PMSM driven asymmetric pump controlled cylinder system [45].

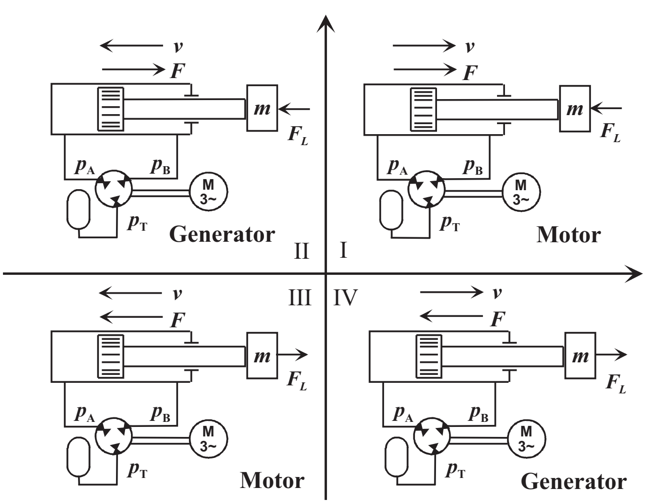

Fig. 13. Four-quadrant operation of the asymmetric pump controlled circuit.

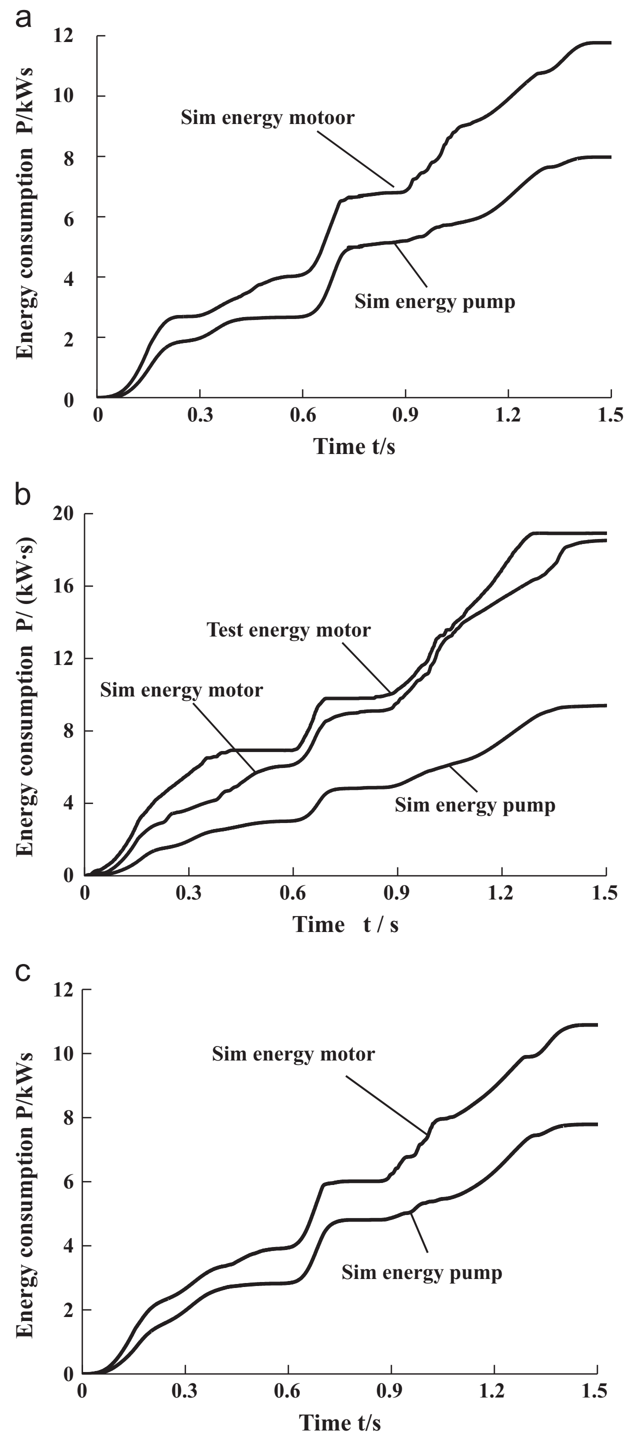

Fig. 14. Energy consumption comparison between differential cylinders controlled by different pumps [46]. (a) Double rods cylinder control system (b) double pump controlled differential cylinder (c) asymmetric pump controlled differential cylinder.

the same energy efficiency performance as the double rods cylinder control system [46].

5. Control of pump controlled cylinder systems

In addition to system exploration, efforts have been put into the control methods to improve the performance of the pump controlled cylinder system. Although the structure of the electro-hydraulic servo systems is simple, these systems are nonlinear, high order, and relatively difficult to control. Moreover varying working condition and parameters further increase the control difficulty. In past decades, many investigations were put forward on the control of electro-hydraulic systems. Majority of them were proposed for valve controlled system or open pump controlled system, but they share the some fundamental electro-hydraulic

principles with closed pump controlled system, especially in the nonlinear control of hydraulic servo systems.

System uncertainties and variable load are two of the electro-hydraulic servo systems' common features. To deal with this problem, many approaches were proposed, such as PID based methods, nonlinear control [47], adaptive control approaches [48–50], sliding mode control approaches [51–53], fuzzy control [54–57], robust control [58], quantitative feedback control [59], and hybrid control methods [60,61]. These methods are also applicable for direct pump controlled systems and some of them already have been applied.

Specifically for direct pump controlled cylinder system, there are also some studies reported. Cho and Burton proposed a feedback-feedforward based simple adaptive control method for direct pump controlled symmetric actuators like double rods cylinders [62]. Wang et al. studied the nonlinear characteristic of hydraulic pump controlled system and applied singular perturbation theory to simplify hydraulic control design [63]. Based on their analysis, a robust control law was proposed. A pump controlled asymmetric cylinder system was used to testify the control laws. Perron et al. proposed a sliding mode controller for a Brushless DC motor driven pump-cylinder system [64]. The time efficiency of the system was improved. Deng et al. studied the cylinder system in rapid-erection system and proposed an intelligent control method based on BP neural network for the prime power source, i.e. diesel engine in this paper [65]. Experiment results showed that the proposed method can effectively stabilize and expedite the erection process and at the same time reduce the fuel consumption. Lee et al. adopted an adaptive fuzzy controller with self-tuning fuzzy sliding-mode compensation for electro-hydraulic system. The method was testified on a direct pump controlled double-rod cylinder system. And results showed that the proposed method has a good performance in the position control of the cylinder [66]. Ahn and Dinh studied the principle of direct pump controlled differential cylinder system and proposed several control methods. An electro-hydraulic test machine was proposed and along with quantitative feedback theory and robust self-tuning quantitative feed controller in Refs. [67,68]. The proposed test machine consists of two AC servo motor driven closed pump controlled differential cylinder systems, in which one cylinder is the force generator, the other cylinder is the disturbance generator. Both cylinders are connected with a spring load system. With the proposed structure, the test machine can be adaptive to various control purposes. Then a self-tuning adaptive control algorithm based on quantitative feedback theory and gradient descend method and back propagation algorithm was employed for the force control of the test machine. The effectiveness of the constructed test machine and the proposed control method were demonstrated through simulation and experiment verifications. In their further research, general fuzzy PID control method, extended Kalman filter based online smart tuning fuzzy PID control algorithm, self-tuning grey predictor based fuzzy PID control algorithm, and back stepping control method were proposed for the force of the test machine [69–73]. In another research, a DC motor driven closed circuit was studied and controlled with quantitative feedback control approach [74]. Chiang applied the direct pump control cylinders into the pitch control of wind turbine [75]. An adaptive fuzzy controller with self-tuning fuzzy sliding-mode compensation was proposed for the system. Zhang et al. employed model following control and resonance ratio control to improve the anti-disturbance performance of system [76]. To addressing the saturation, dead zone nonlinearity, and time variability of the SRM driving pump controlled differential cylinder system, closed loop Iterative Learning Control (ILC) method was also employed to perform robust position control [77].

6. Energy recovery system based on pump controlled cylinder system

One of the most significant merits of the pump controlled system is that the energy recovery becomes applicable. According to the type of the recovered energy, energy recovery technology can be classified into two kinds, recovery system for kinetic energy and recovery system for potential energy. Kinetic energy generally occurs in the regenerative braking operation of travelling system or slewing system. Potential energy occurs in the descending operation of lifting systems where pump controlled cylinder system has been widely applied, such as the boom and stick and arm of the excavator, the bucket of the loader, and short-distant crane and forklift. In conventional valve controlled cylinder systems, the potential energy generated in descending operation of these systems is mostly converted into heat in the main throttle valve, wasting large amount of energy. Based on the pump controlled cylinder structure, such energy can be recovered and reused in either hydraulic storage manner or electric storage manner. Many energy recovery systems have been proposed on the basis of open pump controlled cylinder circuit [78–80]. But few were proposed using closed circuit. A feasible circuit was proposed by Liebherr Company [81], as shown in Fig. 15. A high power differential cylinder composed excavator system which is controlled by two flow displacement variable pumps was studied. The bucket and the stick cylinders are controlled in open loop, and the boom cylinder is controlled in closed loop. The potential energy generated in boom descending are stored by the accumulator connected in the oil compensate port, realizing the integration of the boom drive and control. Field experiment results showed that the manufactured prototype reduced the engine installed power by 25% and meanwhile increased the boom lifting speed and the slewing acceleration by 80%.

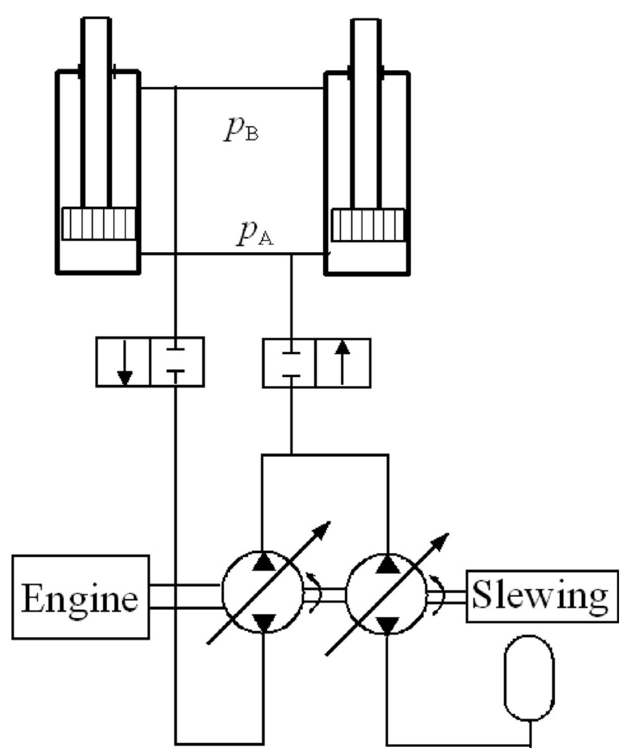

Fig. 15. Accumulator based energy recovery system for hydraulic excavator boom [81].

7. Challenges

7.1. Further verification of asymmetric pump controlled system

Although the development of asymmetric pump has been proved effective in compensating the asymmetric volume of the differential cylinder control system, the generalization of such pump is facing several challenges. The manufacturing complexity of the asymmetric pump is higher than conventional pumps. The application of this new pump have not been fully explored, the performance of asymmetric pump controlled cylinder system in high power or heavy load fields, such as construction machines, has not been verified. To be applicable in high power or heavy load fields, new system scheme is necessary. Furthermore, the dynamic control of this new system lacks investigation.

7.2. Robust control method

Although closed pump controlled system has been recognized as a system with many advantages over pump controlled system and open circuit pump controlled system, its control has not been fully researched yet. Some popular methods like hybrid control have not been applied. And with many control approaches proposed for electro-hydraulic system, comparative studies should be carried out for various applications. Besides, control of load variation and disturbance of such system are still need exploration. Moreover, the resonance between electric drive system and the hydraulic system is a serious problem for the overall stabilization of the system. Conventional notching filter and disturbance estimator combined method suffers from inflexibility and high complexity, which limit the practical application of the method. The dynamic performance of the pump controlled cylinder system, especially the differential cylinder system, is not satisfactory enough which to some extent limits the practical application of the pump controlled system. Therefore novel robust, simple, flexible and practical control methods are demanded.

7.3. New energy recovery system

Currently many studies have been carried out on the open circuit based energy recovery system. But open circuit needs valves in flow control and some schemes even have throttling valves, which degrades the energy efficiency of the system. One reason of why closed circuit based energy recovery system is less researched is that differential cylinder control system suffers from asymmetric flow. But using auxiliary flow balance system will further result in energy consumption. With the development of asymmetric pump, such problem can be settled. And new energy recovery system should be proposed based on the direct pump controlled cylinder system.

Another important issue for energy recovery system is energy storage element. Right now accumulator, battery, and supercapacitor are the three most researched and adopted element but they are still facing various limitations. For now, the accumulator and battery composed hybrid storage solution is a suitable plan [5]. We suggest that the asymmetric pump controlled circuit should be considered since the hybrid energy recovery system can be easily realized due to the four-quadrant operation of the pump and PMSM. Based on circuit shown in Fig. 12, a battery cell can be added as additional energy storage element. When the direction of the piston speed and the direction of the load force are opposite, the PMSM will operate in generator mode, hence the battery can be charged. Because of the servo motor, this system is suitable for hybrid equipments like hybrid construction machines.

8. Conclusion

With the rising concerns for the energy efficiency of fluid power transmission system, energy saving technology for such system is demanding, which lead to the emerging of pump controlled system. Pump controlled cylinder system as the most popular pump controlled system, has been applied in many heavy working conditions, the energy efficiency of which matters a lot to the efficiency of the overall equipment. This work gathers and summarizes the development and the latest status of the pump controlled cylinder technology, which are scattered in various literatures. Different types of hydraulic circuits are summarized for the convenience of researchers. Although this technology is still facing limitations and challenges, new solutions are coming up. With the improvement of energy efficiency and dynamic performance, it is identical that the direct pump controlled cylinder system as a novel electro-hydraulic actuator system will have more and more applications. And in the end, it is hoped that this paper will be a valuable source of information for researchers, machine designers and manufactures.

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